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INVARIANT-MASS AND γ -RAY SPECTROSCOPY USING SECONDARY, RADIOACTIVE ION BEAMS * **

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Coulomb excitation of secondary beams ($5 \leq Z \leq 20$) at energies around 250 A·MeV was explored at GSI. For low-lying states, γ -ray spectroscopy was utilized, while high-lying excitations were investigated by means of invariant-mass spectroscopy.

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1. Introduction

Since a couple of years it is possible to study properties of nuclei far off stability by using radioactive beams. A recent experiment at GSI was carried out to do spectroscopy in complete kinematics on medium-heavy ($5 \leq Z \leq 20$), neutron-rich ions at more than 200 A·MeV. At these energies electromagnetic excitation is possible up to energies of the giant resonances.

One of the motivations for this experiment was to investigate multipole strength distributions (E1, E2) of the excitations. Besides ground state properties, this is the richest source of information on the effective interaction in nuclear matter. Most commonly, the RPA is used to describe nuclear excitations: Shell-model RPA uses a phenomenological mean field and the parametrized p-h interaction is adjusted to experimental excitation spectra. In the more fundamental self-consistent RPA, the parameters of the effective two-body interactions (e.g. Skyrme or Gogny type) can be obtained from groundstate properties. Parameter sets accounting properly for the observed groundstate properties, however, are not unique and information from excited states needs to be included again. Such information from giant resonances, so far, was only deduced for stable nuclei, *i.e.* essentially for symmetric nuclear matter at normal density.

These two degrees of freedom, asymmetry and density, can be varied when going to unstable nuclei, the latter because of diffused surfaces appearing in weakly bound nuclei near the n-dripline (neutron “halos” / “skins”). In the excitation of exotic nuclei, new effects are supposed to occur:

- a considerable re-distribution in the E1 multipole strength (towards lower excitation energies: “pygmy resonances”, “soft dipole mode”) due to a decoupling of loosely bound valence neutrons from the core (vibration of skin- / halo-neutrons versus the core);
- significant rearrangements in the single-particle level structure in asymmetric nuclei, thus influencing the multipole strength distributions. The $2s_{1/2} \leftrightarrow 1p_{1/2}$ level inversion around $A \approx 10$ and the vanishing $N = 20$ shell gap are already known examples;
- in turn deformations arise, *i.e.* deformed shell gaps, yielding splittings of the multipole strength distributions. The latter effect can as well be studied by means of γ -ray spectroscopy of low-lying states, where *e.g.*, the B(E2) values to first excited states of even-even nuclei give information about quadrupole deformations.

2. Experimental method

It has been shown in earlier experiments with stable beams [1, 2], that Coulomb excitation of heavy ion projectiles at several 100 A·MeV impinging on heavy target nuclei is a suitable method to excite giant resonances, even in their higher phonon states.

The electromagnetic pulse seen by the fast projectile passing the target nucleus can be interpreted as a flux of virtual photons (Weizsäcker-Williams method) [3]. The photon spectrum steeply decreases at high energies and as a thumb rule, the maximum excitation energy reachable can be estimated as

$$E_{\max}/\text{MeV} \approx 20 \cdot \beta \cdot \gamma / (b_{\min}/\text{fm}) \quad \text{“adiabatic cutoff”,} \quad (1)$$

with $\beta = \frac{v}{c}$, the Lorentz parameter γ and the minimum impact parameter b_{\min} : *e.g.*, for the system ^{18}O on ^{208}Pb , one obtains $E_{\max} \approx 15$ MeV for bombarding energies of 250 A·MeV, and $E_{\max} \approx 30$ MeV for 800 A·MeV, respectively.

In the present experiment, radioactive secondary beams were produced by fragmenting a primary 330 A·MeV ^{50}Ti beam with an average intensity of $2 \cdot 10^8 \text{ s}^{-1}$ particles from SIS at GSI on a 4 g/cm² Be target. The fragments were selected for a magnetic rigidity of $B\rho = 5.6$ Tm by the fragment separator FRS, corresponding to mass-to-charge ratios of $2 \leq A/Z \leq 2.6$ at energies of approximately $200 \text{ A} \cdot \text{MeV} \leq E_{\text{beam}} \leq 300 \text{ A} \cdot \text{MeV}$ (see Fig. 1).

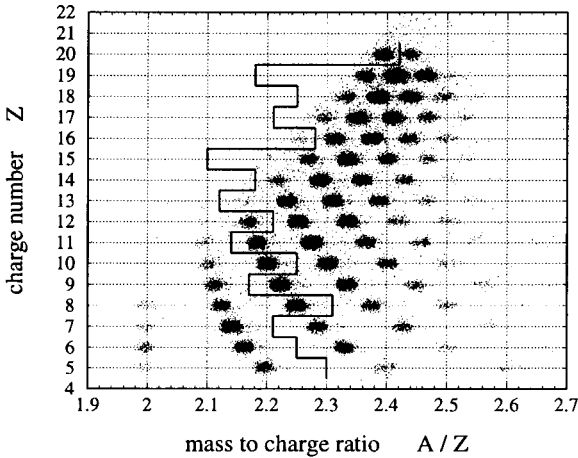


Fig. 1. Composition of the mixed secondary beams, containing approximately 10 stable and 25 unstable isotopes. The borderline of stability is shown as a solid line. The nuclear charge is measured via energy loss in PIN diodes, the mass-to-charge ratio is obtained from time-of-flight.

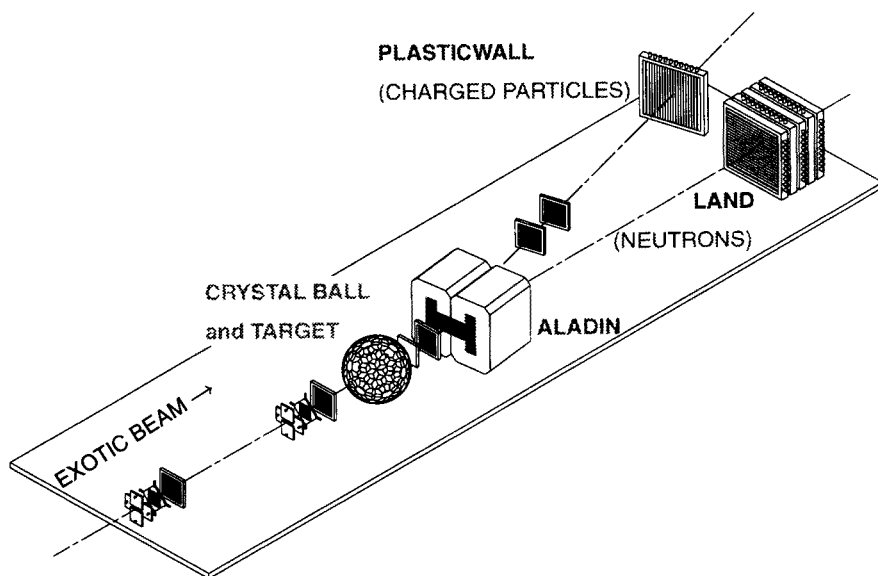


Fig. 2. Schematical view of the experimental setup (see text).

The mixed secondary beams were transferred to the experimental area with intensities of $\sim 2 \cdot 10^4 \text{ s}^{-1}$ and identified with the setup shown in Fig. 2, determining the nuclear charge by the energy loss in PIN diodes and the nuclear mass number by time-of-flight measured with plastic scintillators. The beam hit the target in the center of the Darmstadt-Heidelberg Crystal Ball, which consists of 162 NaI detectors covering the full solid angle, except for the beamline. A large dipole magnet (ALADIN) deflects the beam or fragments by about 20° . The deflection angle is measured with two scintillating fibre detectors, thus, in combination with the measurement of the time-of-flight (Plastic Wall) and of the scattering angle in the target with multiwire chambers, allowing to resolve different masses after reactions in the target. Because of the ions' high velocity ($\beta \approx 0.6$), neutrons emitted by excited fragments are focussed in forward direction and are detected with high efficiency in the large area neutron detector (LAND). This is important, as giant resonances mostly decay by emission of at least one neutron.

The measurements were carried out with Pb ($\sim 1 \text{ g/cm}^2$), C target ($\sim 0.5 \text{ g/cm}^2$) and without target in order to disentangle Coulomb and nuclear excitations and in order to account for background reactions, respectively.

3. Results

Differential cross sections with respect to excitation energy of the projectile were obtained by utilising the Lorentz-invariant quantity

$$M^2 = (m_{\text{proj.}} + E^*)^2 = \left(\sum_j P_j \right)^2 \quad (\text{invariant mass}), \quad (2)$$

where P_j denotes the 4-momenta of the fragment and the neutrons, $m_{\text{proj.}}$ and E^* denote the groundstate mass and excitation energy of the projectile, respectively. The residual fragment is not necessarily in its groundstate after neutron emission, and its remaining excitation energy is released by γ de-excitation cascades. Above relation can conveniently be rewritten as [4]

$$M = \sqrt{\sum_j m_{\text{proj.}}^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j \cos(\vartheta_{ij}))} + E_F^* \quad (3)$$

involving groundstate masses m_j , velocities β_i and relative angles ϑ_{ij} between neutrons and between neutrons and the fragment. The residual energy E_F^* of the fragment can be obtained from the total γ -ray energy released by the fragment, if evaluated in the projectile rest frame; the small fragment recoil energy is neglected.

The spectra were normalized to the target thickness and number of incident particles. The background from reactions outside the target was subtracted using the run without target, the contribution due to nuclear excitation in the target was subtracted using the C target run and scaling it with a parametrization accounting for the different nuclear radii of ^{208}Pb and ^{12}C [5]. As mentioned in the introduction, Coulomb excitation can be interpreted as absorption of virtual photons. Thus, the Coulomb excitation data can be compared to photo absorption data, by accounting for the distribution of the virtual photon spectrum. Using this correspondence, as two examples, preliminary data of the stable ^{18}O and the unstable ^{46}K are compared to calculated excitation spectra from photoabsorption data of ^{18}O [6] and of the semi-magic isotope ^{39}K [7], respectively (Fig. 3). For the experimental data, a coincidence of beam fragments with neutrons and γ -rays, which is the trigger condition with the lowest amount of background events, and an unchanged nuclear charge of the projectile were required. Consequently, the data are compared to the (γ, n) part of the photoabsorption cross section.

The measured data show large errorbars due to the low counting statistics and due to the contribution of background and nuclear interactions in the uncorrected data, which is of the order of 70 ... 80% of the events measured with the Pb target. Thus, the shown cross sections do not allow a

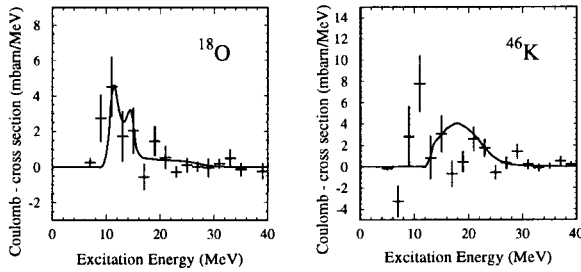


Fig. 3. Measured Coulomb excitation cross sections (preliminary) for the isotopes ^{18}O and ^{46}K , compared with calculated cross sections using (γ, n) experimental photoabsorption data from ^{18}O and ^{39}K , respectively.

quantitative physical interpretation. Nevertheless, for ^{18}O the low-lying E1 strength around an excitation energy of ~ 10 MeV is qualitatively observed. This strength was attributed in [6] to the fact that two valence neutrons surrounding the ^{16}O core. For ^{46}K , when compared to the ^{39}K data, some excitation strength below the giant dipole resonance around 20 MeV can be seen, which might be attributed to some soft dipole contribution originating in the 7 neutrons added to the $N = 20$ shell.

Fig. 4 shows results for the γ -spectroscopy of low-lying levels in $^{27,28}\text{Mg}$ [8]. Because the excitation energies are below the neutron binding energy, only coincidences of fragments with γ -rays were taken into account. The Crystal Ball is very well suited for γ -spectroscopy of relativistic projectiles:

- The full energy efficiency of NaI is rather high and can even be increased by adding up energies deposited in neighbouring crystals;
- The moderate energy resolution of about 7% at 1.33 MeV is no severe disadvantage, as the Doppler-broadening of the measured γ -rays at velocities of $\beta \approx 0.6$ is of the same order. Coulomb excitation in these light nuclei only populates few levels, being usually spread widely enough to compensate for this resolution.

The excitation of the first 2^+ -states with the Pb target is clearly seen when looking at events at angles corresponding to small impact parameters but still being below the grazing angle of approximately 23 mrad (Fig. 4, right-hand part). These γ -transitions are absent in the spectra taken for small scattering angles, *i.e.* large impact parameters (Fig. 4, left-hand part).

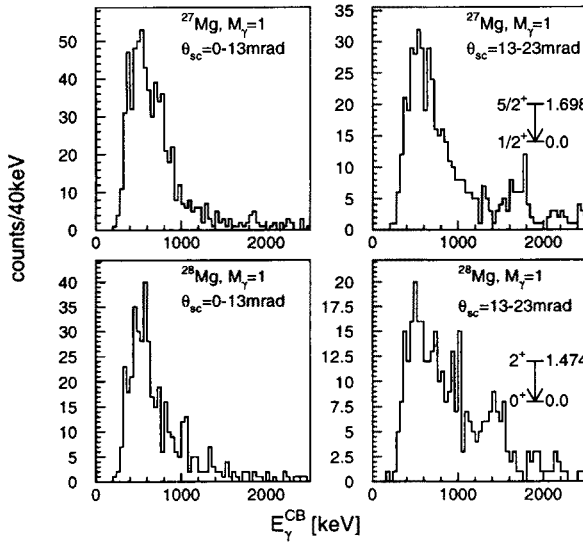


Fig. 4. Measured γ -spectra (corrected for Doppler-shift) from $^{27,28}\text{Mg}$ beams excited on Pb target in two different regimes of scattering angles Θ_{sc} . The required hit multiplicity in the Crystal Ball was $M_\gamma = 1$. The levels for the 1698 keV and 1474 keV E2 transitions to the groundstates are indicated.

4. Conclusion

It was shown, that electromagnetic excitation in radioactive nuclei can be investigated in kinematically complete experiments, using secondary, mixed beams from SIS/FRS at GSI at energies of more than 200 A-MeV. This can be done with “conventional” γ -spectroscopy for the first excited levels as well as for higher excitation energies using invariant-mass analysis, including neutron and fragment detection. This first attempt at GSI on spectroscopy of radioactive neutron-rich nuclei in the region ($5 \leq Z \leq 20$) was suffering from poor counting statistics due to low primary beam intensities, which was distributed on approximately 40 secondary isotopes. A second experiment in April 1997 will take profit from higher primary intensities and a concentration on fewer secondary beams, especially the oxygen isotopes near the dripline ($^{22,24}\text{O}$). Moreover, two different bombarding energies will be used, in order to disentangle contributions from E1 and E2 excitation.

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